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Estimating Vegetation Amount from Visible and Near Infrared Reflectances

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We consider the inference of vegetation status from measurements in the visible and near infrared, in the presence of variable soil reflectance. There are two cases, depending on spatial variability within the instrumental field of view. The first, or "field" case, assumes a spatially uniform vegetation canopy, which is treated in a simple two-stream approximation. In this case, appropriate to Landsat or SPOT data, a value for leaf area index (LAI) may be obtained from reflectance measurements in the visible and near infrared. The second, or "mixed pixel" case, applies for spatial inhomogeneity on a scale larger than individual plant groupings, that is, surface types with varying amounts of vegetation and bare soil. In this case, appropriate to AVHRR observations of agricultural areas, a fractional cover f, *corresponding to dense vegetation, may be obtained from the two measurements. A leaf vegetation index* V_L, *having limits 0 and 1, is introduced for the field case. For a thin canopy (LAI* $\ll$ *1) the leaf vegetation index is shown to equal the vegetation fraction* f. *Analysis results are compared to commonly used vegetation indices.*

INTRODUCTION

Much research has been carried out with the goal of inferring vegetation amount from remote measurements in the visible and near infrared. The effect of soil reflectance on remote assessment of vegetation conditions has been reviewed in a discussion by Huete (1989). More recently, Baret and Guyot (1991) have used the SAIL model (Verhoef, 1984) to evaluate the sensitivity of several vegetation index formulas to approximations and to soil reflectance and leaf inclination. Earlier, Perry and Lautenschlager (1984) had described the mathematical relationships among a number of vegetation indices. We refer the reader to these excellent references for background information and for discussions of various limitations of formulas for the vegetation / soil problem. In this article, we develop simple relationships between remote observations in the visible and near infrared, as exemplified by the NOAA Advanced Very High Resolution Radiometers (AVHRRs), or the Landsat and SPOT sensors, and vegetation cover. There are two cases, which we call the "field" case and the "mixed pixel" case. In the field case, we assume that vegetation cover is uniform within an instrumental field of view, so that spatial inhomogeneity may be neglected, and treat the canopy as a spatially uniform layer above the soil. This case generally applies to Landsat and SPOT observations. In the mixed pixel case, spatial variability is assumed, corresponding to an AVHRR observation of a number of fields with varying amounts of vegetation and bare soil, but with details of individual fields unknown. Throughout the discussion we ignore questions of atmospheric transmittance and angular effects, which require additional formulations (Holben et al., 1986).

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THE FIELD CASE

We consider measurements of a vegetation canopy from sufficient distance that variability associated with individual leaves and plant structure may be neglected. The problem we address is well represented in Figure 1 by Huete (1988). The goal is to estimate vegetation cover for a homogeneous area, such as an agricultural field, from remote measurements in the visible and near infrared, that is, from reflectance as given in Figure 1. Graphs similar to Figure 1 have been obtained by Baret and Guyot (1991), using the SAIL model of Verhoef (1984), and by Richardson and Wiegand (1991), by treating individual components of the plant / soil / shadow structure. Clevers (1988; 1989) has used a semiempirical model to estimate leaf area index from reflectance data. In this study we consider a vegetation canopy with leaf area index LAI = (leaf area) / (ground surface area), covering a soil of reflectance $r_s(\lambda)$, where λ is the wavelength. We will treat the interaction of radiation with vegetation in a very simple two-stream approximation, although many more complete and sophisticated methods are available (Asrar, 1989). I am indebted to W. Verhoef for suggesting this approach, which corrects an error in the original version of the manuscript. Thus the downwelling radiation I and the upwelling radiation J at wavelength λ are described by the equations

$$\frac{dI}{dl} = -\alpha I + \beta J, \quad \frac{dJ}{dl} = \alpha J - \beta I, \tag{1}$$

where $\alpha(\lambda)$ is an absorption coefficient, $\beta(\lambda)$ is the scattering (reflection) coefficient, and dl is an increment in leaf area index, with l measured downward from the top of the canopy. By differentiating each equation with respect to l and substituting using Eq. (1), we find that both I and J satisfy equations of the form $d^2I/dl^2 = (\alpha^2 - \beta^2)I = c(\lambda)^2 I$, which defines c. Then I and J are given by $I = a_1e^{-cl} + a_2e^{cl}$ and $J = a_3e^{-cl} + a_4e^{cl}$, where $a_1 \cdot\cdot\cdot a_4$ are to be determined.

Two equations relating the a's may be found by substituting these solutions into the first-order equations [Eq. (1)]. Two additional equations result from the boundary conditions. At the top of the canopy ($l = 0$), the downward radiation must equal the downward incident radiation. In order to deal with reflectances, we set the incident radiation to 1, so that the boundary condition

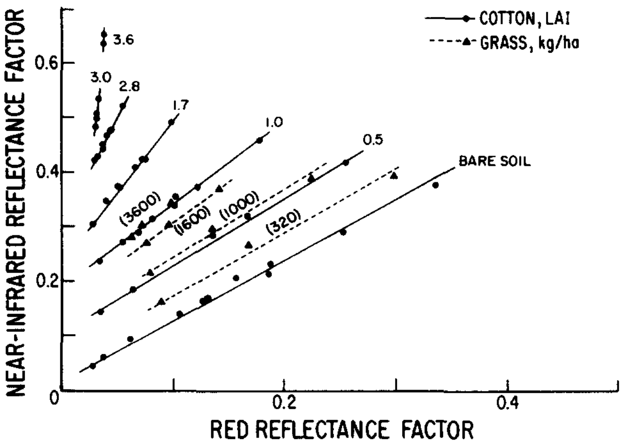

Figure 1. Observed vegetation isolines for various canopy densities of cotton and grass with differing soil background conditions. Numbers in parenthesis represent grass phytomass. From Huete (1988), reproduced by permission of Elsevier Science Publishing.

is $a_1 + a_2 = 1$. The fourth equation expresses the relation between downward radiation at the bottom of the canopy at depth LAI, and the upward radiation which is reflected from the underlying soil with reflectance $r_s(\lambda)$. Thus $J(\mathrm{LAI}) = r_s \cdot I(\mathrm{LAI})$. By solving these four equations, we may find the upward radiation for unit incident radiation, that is, the reflectance $R(\lambda)$:

$$R(\lambda) = \{[c(\lambda) - \alpha(\lambda)] / \beta(\lambda) + [\alpha(\lambda) + c(\lambda)] / \beta(\lambda) \cdot D(\lambda)\} / [1 + D(\lambda)], \tag{2}$$

where

$$D(\lambda) = \frac{[c(\lambda) - \alpha(\lambda)] / \beta(\lambda) + r_s(\lambda)}{[c(\lambda) + \alpha(\lambda)] / \beta(\lambda) - r_s(\lambda)} \cdot e^{-2c(\lambda)\cdot \mathrm{LAI}}. \tag{3}$$

It is desirable to express the reflectance in terms of quantities which we may estimate readily from experimental data such as that of Huete et al. in Figure 1. To this aim we evaluate the reflectance of a dense canopy (LAI = ∞), which yields $D(\lambda) = 0$, and $r_\infty(\lambda) = [c(\lambda) - \alpha(\lambda)] / \beta(\lambda)$. To simplify, we define another variable $u(\lambda) = [c(\lambda) + \alpha(\lambda)] / \beta(\lambda)$. Then the reflectance of the soil and canopy is given by

$$R(\lambda) = [r_\infty + u \cdot D] / (1 + D), \tag{4}$$

where

$$D = \frac{r_s - r_\infty}{u - r_s} \cdot e^{-2c\cdot \mathrm{LAI}}. \tag{5}$$

The variable c may be estimated readily from measurements of the attenuation of radiation with depth in a canopy. However, the variable u is more difficult to determine, representing a function of attenuation and scattering. We shall eliminate the effect of this term, formally by letting u go to infinity, which does not affect the value of R at zero or infinite canopy depth. Then

$$R = r_\infty + (r_s - r_\infty) \cdot e^{-2c \cdot \mathrm{LAI}}. \tag{6}$$

We demonstrate the correspondence of this formulation to Figure 1 by choosing evenly spaced points along the line representing variability of soil brightness, the soil line

$$r_{s2} = a \cdot r_{s1} + b, \tag{7}$$

where we adopt subscripts for wavelength dependence, with 1 for visible and 2 for near infrared. We have selected LAI values and numerical values for constants r_∞, c, etc. appropriate to Figure 1. These values are: $a = 1.13$, $b = 0.006$, $c_1 = 0.56$, $c_2 = 0.28$, $r_{\infty 1} = 0.03$, $r_{\infty 2} = 0.68$.

Figure 2 illustrates computed reflectances as a function of these soil and vegetation parameters, showing general agreement with Huete's data, and with graphs of Baret and Guyot and of Richardson and Wiegand (not shown). Evidently Eq. (6) captures the essential relationship between visible and near infrared reflectances and leaf area index. However, this formulation is inadequate for remote sensing application, which is an inverse problem requiring estimation of soil and vegetation parameters from remote measurements R_1 and R_2, rather than values of R_1 and R_2, given the soil reflectance and LAI information. To this aim we solve Eq. (6) for the soil reflectance r_{si} in channels $i = 1,2$, and substitute the resulting values into Eq. (7), finding

$$r_{\infty 2} + (R_2 - r_{\infty 2}) \cdot e^{2c_2\,\mathrm{LAI}} = a[r_{\infty 1} + (R_1 - r_{\infty 1}) \cdot e^{2c_1\,\mathrm{LAI}}] + b. \tag{8}$$

It is convenient to make the substitution $x = e^{2c_2\,\mathrm{LAI}}$, so that $e^{2c_1\,\mathrm{LAI}} = x^{c_1/c_2}$, and a polynomial equation results. Although this equation may be solved explicitly for LAI if c_1/c_2 has values 1, 2, 3, or 4, or their inverses (Abramowitz and Stegun, 1964), more generally a numerical solution is necessary, for example, by Newton's method. Thus one generates a lookup table of LAI values for an array of R_1 and R_2 values, and interpolates within this array as needed when evaluating remotely sensed observations. For the values chosen

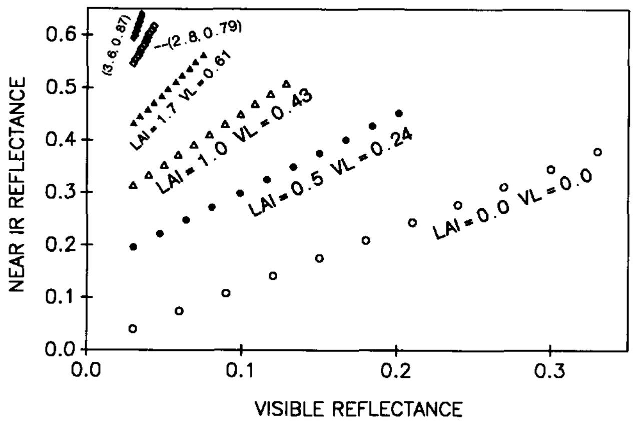

Figure 2. Visible and near infrared reflectances for values of leaf area index corresponding to Figure 1, as calculated from Eq. (1), for a set of 11 soil backgrounds. Values of the LAI based vegetation index V_L are also given.

to produce Figure 2, a quadratic equation results, and the solution is given by

$$\mathrm{LAI} = \frac{1}{2c_2}\ln\Big(\{r_{\infty 2} - R_2 - [(r_{\infty 2} - R_2)^2 - 4(r_{\infty 2} - ar_{\infty 1} - b)\cdot(R_1 - r_{\infty 1})]^{1/2}\} [2(R_1 - r_{\infty 1})]^{-1}\Big). \tag{9}$$

This completes the solution, subject to the assumptions given here and described in Huete's work. However, it is desirable to introduce a scaled variable which may be related to results which follow for the mixed pixel case, as well as permitting comparison with other vegetation index expressions. We define a leaf vegetation index V_L, a function of LAI, by

$$V_L = 1 - e^{-2c_2\,\mathrm{LAI}}, \tag{10}$$

which has values $V_L = 0$ for $\mathrm{LAI} = 0$ and $V_L = 1$ for $\mathrm{LAI} = \infty$. Values of V_L are shown in Figure 2 next to the LAI values. If one elects to use remote sensing to infer V_L instead of LAI, then LAI may be obtained by

$$\mathrm{LAI} = -(1/2c_2)\ln(1 - V_L). \tag{11}$$

THE MIXED PIXEL CASE

For large area agricultural assessment, the AVHRR is a useful tool, despite the 120 hectare field of view for each picture element. However, in many cases the AVHRR measurements correspond to a mixture of bare soil and growing fields at various stages of canopy cover. Of course, no general solution is possible from the two measurements in the visible and near infrared, as two measurements are not sufficient to infer more than two unknowns. We simplify by assuming that the reflectance measurements correspond to the sum from two surfaces, a dense vegetation cover with fractional cover, f, and bare soil with fraction, $1-f$. Such mixture models have been used frequently (e.g., Richardson and Wiegand, 1991). Then by straightforward analysis we find the value for f resulting from the heterogeneous surface:

$$f=\frac{R_2-aR_1-b}{r_{\infty 2}-ar_{\infty 1}-b}, \tag{12}$$

where the terms have been defined previously. Evidently f is 0.0 on the soil line $R_2=aR_1+b$, and f is 1.0 for visible and near infrared reflectances of $r_{\infty 1}$, $r_{\infty 2}$. Lines of constant f are parallel to the soil line.

RELATIONSHIP OF V_L AND f FOR SPARSE VEGETATION

When vegetation density is very low, the reflected radiation is dominated by soil contributions, and the effect of multiple reflections within the plant canopy is greatly reduced. In this limit the location of plants within the instrumental field of view should have no effect, and we expect a relationship between V_L, which treats plant cover as a uniform (but thin) layer, and f, which treats the reflectance as a sum from one area of bare soil and another of vegetation. To find the relationship, we expand Eq. (10) for small LAI, that is, for c_2 LAI $<<1$, finding

$$V_L=2c_2\ \mathrm{LAI}. \tag{13}$$

Similarly, we expand Eq. (6) for small LAI for both visible and near infrared, and substitute the results into Eq. (12) for f, finding

$$f=\frac{r_{s2}+2c_2r_{\infty 2}\ \mathrm{LAI}-a[r_{s1}+2c_1r_{\infty 1}\ \mathrm{LAI}]-b}{r_{\infty 2}-ar_{\infty 1}-b}$$
$$=2c_2\ \mathrm{LAI}\cdot\frac{1-a\cdot c_1\cdot r_{\infty 1}/(c_2\cdot r_{\infty 2})}{1-(a\cdot r_{\infty 1}+b)}, \tag{14}$$

where we have used the soil line equation [Eq. (7)]. For the constant values given previously, the fraction in the lower expression is $0.975/0.96=1.02$. We conclude that the mixed pixel result for f and the canopy layer result for V_L are essentially equal for sparse vegetation cover. The equivalence is not valid as the amount of vegetation increases and interactions within the canopy become important. Thus an isolated tree surrounded by bare soil produces different radiances from an equal number of leaves evenly distributed over the same area.

It is worthwhile to compare the formulations for V_L and f to other commonly used vegetation indices.

RELATIONSHIP TO OTHER VEGETATION INDICES

We relate V_L to several other vegetation indices in order to establish the significance of the parameters in the description by Eqs. (6) and (12). The normalized difference vegetation index (NDVI) of Rouse et al. (1974) is given by

$$\mathrm{NDVI}=\frac{R_2-R_1}{R_2+R_1}. \tag{15}$$

The perpendicular vegetation index (PVI) (Richardson and Wiegand, 1977) is given by

$$\mathrm{PVI}=\frac{1}{(a^2+1)^{1/2}}(R_2-aR_1-b). \tag{16}$$

We note that PVI differs from f [Eq. (12)] only by a scaling factor. The soil adjusted vegetation index (SAVI) (Huete, 1988) is given by

$$\mathrm{SAVI}=\frac{(R_2-R_1)\cdot(1+L)}{(R_2+R_1+L)}, \tag{17}$$

where Huete recommends the value $L=0.5$. Baret and Guyot (1991) developed the transformed soil adapted vegetation index (TSAVI), given by

$$\mathrm{TSAVI}=\frac{a(R_2-aR_1+b)}{[aR_2+R_1-ab+X(1+a^2)]}, \tag{18}$$

where $X=0.08$ is suggested. Figures 3a–d illustrate the range of values resulting for the respective vegetation indices for the data points selected in Figure 2. Constants required for the various vegetation indices, including V_L and the vegetation fraction f, are identified in Table 1. By comparing the ranges of the various vegetation indices, we identify the significance of these constants:

1. The soil line constants establish a zero point for the associated vegetation index, except for SAVI.

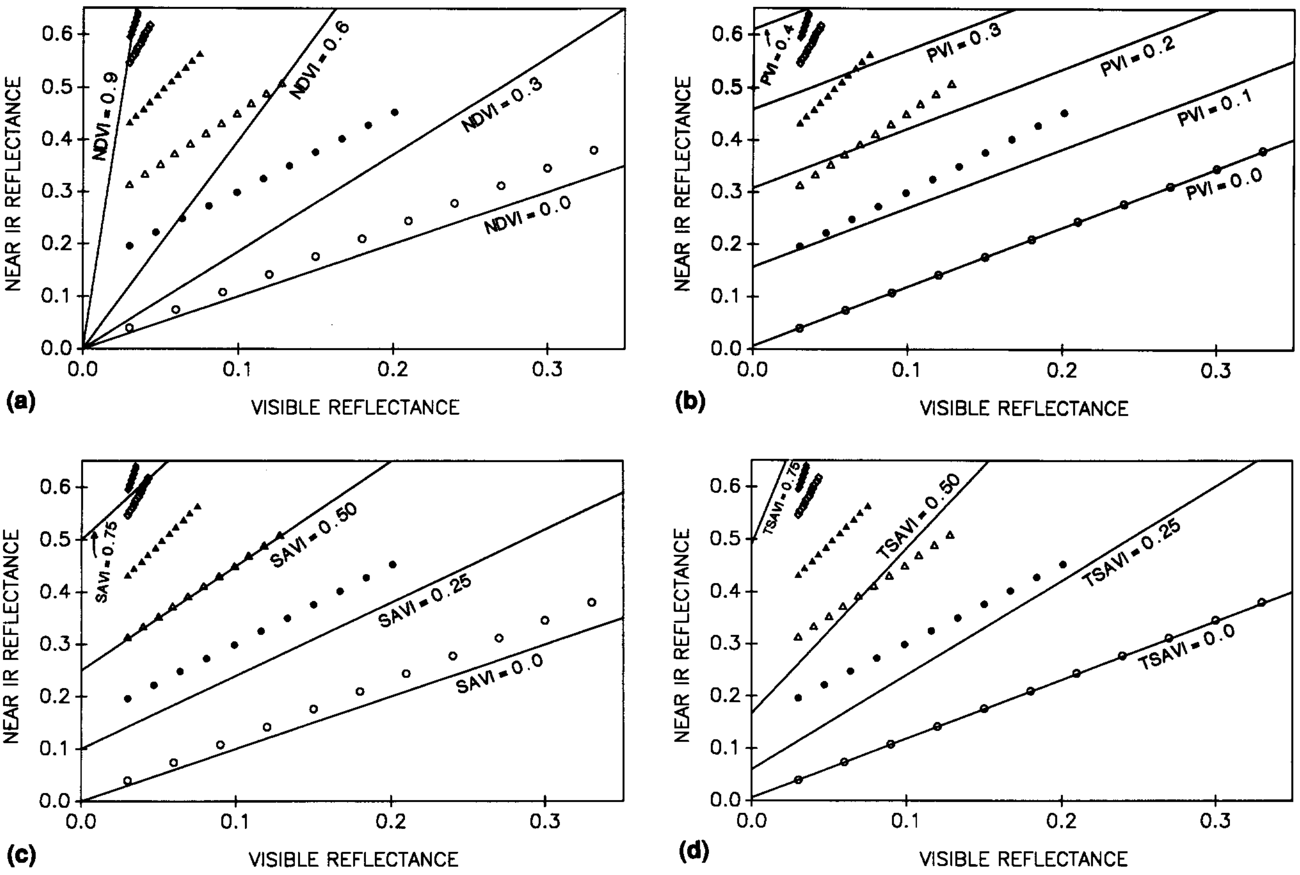

Figure 3. Illustrative values of NDVI (a), PVI (b), SAVI (c), and TSAVI (d) are shown superposed on calculated reflectances from Figure 2.

2. The reflectances $r_{\infty 1}$ and $r_{\infty 2}$ serve to place an upper bound of 1.0 on V_L and f for a totally vegetated surface (LAI = ∞), whereas the other vegetation indices are unscaled.
3. The ratio c_1 / c_2 determines the rotation of the LAI line in Figure 1, as leaf area varies.
4. The magnitudes of c_1 and c_2 are scaled to the physical quantity LAI (area / area). Otherwise we could double LAI and halve c_1 and c_2 without affecting the calculated reflectances in Figures 2 and 3.

It is true that the expressions for V_L and f require knowledge of a number of constants in order to yield answers for vegetation conditions over large areas. However, we believe that an atlas or database of such constants is needed at a regional scale for further progress in global description of processes at the earth's surface (Price, 1990).

CONCLUSION

We suggest that the field description is appropriate for high spatial resolution data from Land-

Table 1. Comparison of Data Requirements and Range of Values for Different Vegetation Indices

	Constants Required							
Index	*a*	*b*	$r_{\infty 1}$	$r_{\infty 2}$	*X or L*	c_1	c_2	*Range of Values (Fig. 1)*
NDVI								0.07–0.88
PVI	x	x						0.00–0.38
SAVI	x	x			x			0.03–0.75
TSAVI	x	x			x			0.00–0.75
V_L	x	x	x	x		x	x	0.00–0.87
f	x	x	x	x				0.00–0.82

sat or SPOT and for surface observations, although a better treatment of the interaction of radiation with vegetation is clearly desirable. Evidently experimental data for the constants r_∞ and c are needed for various crops, shrubs, trees, etc. We would hope that multispectral observations can be used to identify the vegetation type, and thus assure selection of the proper value for these constants. The mixed pixel description is more suitable for AVHRR observations. For such low resolution data, one must consider other sources of information, such as from Landsat or SPOT, or ground observations, to provide knowledge of statistical distribution of vegetation conditions within each 1.1 km pixel. In either case the formulations presented here provide a direct relationship between observed reflectances and well defined vegetation parameters.

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